

NUMERICAL PREDICTION AND OPTIMIZATION OF DEPRESSURIZED SODIUM-
WATER REACTION EXPERIMENT WITH COUNTER-FLOW DIFFUSION FLAME

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ABSTRACT

Sodium-water reaction (SWR) is a design basis accident of a Sodium Fast Reactor (SFR). A breach of the heat transfer tube in a steam generator (SG) results in contact of liquid sodium with water. Typical phenomenon is that the pressurized water blows off, vaporizes and mixes with the liquid sodium.

In this paper, a new computer program has been developed and the SWR in a counter-flow diffusion flame is studied by a numerical simulations and an experiment. The experiment is designed with the numerical simulation so that the stable reaction flame is maintained for long time and physical and chemical quantities are measured. From the comparison of analysis and experiment, there exist discrepancies that may be caused by the assumptions of chemical reaction. Hence, a new experiment is proposed to enhance the measurement accuracy and to investigate the reason of the disagreement. The authors propose a depressurized experiment. With the depressurization, it is expected the flame location can be controlled and the reaction region becomes thicker because of decrease in reactant gas density.

NOMENCLATURE

C_p specific heat
 C_u Cunningham correction factor
 D_k Diffusion coefficient

F Heat transferred by gas diffusion
 g_i i-th component of gravity vector
 k identify chemical species
 $n(v)$ aerosol number density with its volume v
 p pressure
 Q_R radiation heat transfer per unit volume
 S_k mass production per unit volume
 S aerosol production rate
 T temperature
 t time
 \mathbf{u} velocity vector
 \mathbf{U} terminal velocity vector of particle
 u_i i-th component of velocity vector
 Y_k molar mass density
 β aerosol coagulation rate
 ε emissivity
 λ thermal conductivity
 ν kinetic viscosity
 ρ density
 σ Stephan-Boltzman constant

1. INTRODUCTION

1.1 Background and Purpose

In a sodium-cooled fast reactor (SFR), liquid sodium is used as heat transfer fluid to carry the energy from the reactor

core to the steam generation (SG) system. The liquid sodium has an excellent heat transport capability and a large safety margin to the boiling point (1153K) at an atmospheric pressure. On the other hand, it has chemical reactivity in contact with water vapor. One of the design basis accidents of the SFR is the water leakage into liquid sodium through a heat transfer tube of SGs, i.e., sodium-water reaction (SWR).

Consequently, coupled phenomena of chemical reaction and thermal-hydraulics of sodium and water vapor are of importance from the safety viewpoint. Large-scale experiment series of SWR were performed in Japan (Tanabe and Wchi, 1990). However, the SWR phenomena are generally complex and the experimental measurement technology is not well matured. Therefore, a numerical simulation is used to investigate the coupled phenomena and local quantities such as mass concentrations flow velocities, and temperatures.

According to Takata and Yamaguchi et al. (2005), two chemical reaction types are considered, i.e. a surface reaction and a gas-phase reaction. In the initial phase of the SG tube failure accident, the temperature is well below the sodium boiling point and little sodium vapor exists. Therefore, the water vapor and liquid sodium react at the gas-liquid interface. It is the surface reaction that occurs at the liquid sodium surface. Subsequently, the liquid sodium is heated up by the exothermic reaction. At this stage, sodium vaporizes and the sodium vapor and the water vapor encounter. It results in the gas-phase reaction. In general, most of the sodium remains in the liquid phase because of a large amount of the liquid sodium inventory.

This paper deals with a numerical simulation and an SWR experiment in the gas phase. It is advantageous to study the gas-phase reaction to understand the characteristics of the SWR. In the gas-phase reaction, one can calculate spatial distributions of the reactants and product including airborne particulates as well as temperature by solving conservation equations. For validating the numerical method, a counter-flow diffusion flame experiment was performed.(Yamaguchi and Takata et al., 2006) Numerically obtained spatial distributions of quantities are compared with the experimental measurement. According to the comparison, discrepancies are found between experiment and analysis. Here a new experiment is proposed to enhance the measurement accuracy of the chemical and thermal quantities, that is an experiment in depressurized condition.

1.2 Sketch of the SWR

The pressure of the water side is approximately 17 MPa and that of sodium side is 0.2MPa. The temperatures in the sodium side are 625K and 743K for cold leg and hot leg, respectively. The sodium is in liquid phase because the boiling temperature is greater than the system temperature by 500 K. A breach of a heat transfer tube in the SG results in

contact of the liquid sodium with the water. Therefore, sudden influx of the water and steam into liquid sodium takes place. The water changes into the vapor phase by sudden depressurization in quite a short time. Typical phenomenon is that the pressurized water and steam blows off and mixes with the liquid sodium where many heat transfer tubes exist. At the interface of the liquid sodium and the water vapor, the SWR takes place and reaction heat and reaction products, i.e. sodium hydroxide and hydrogen mostly are generated.

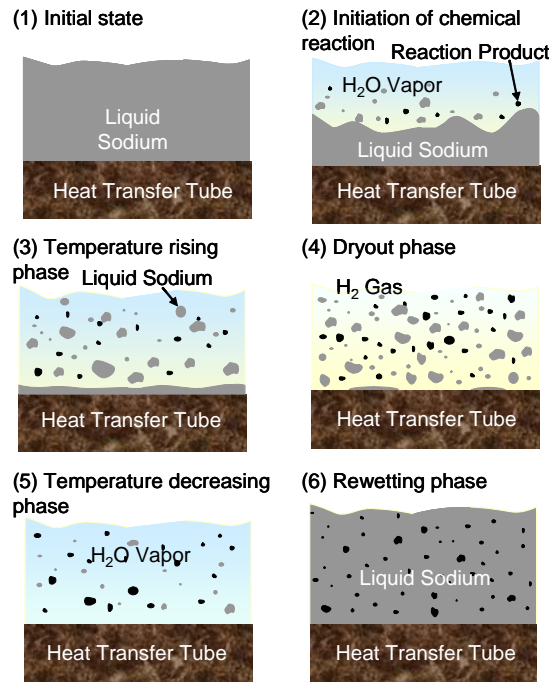


Fig. 1 Sketch of the sodium water reaction phases.

A sketch of the reaction zone around the tube surface is shown in Fig. 1. At the interface of bulk sodium and water vapor jet, the relative velocity is large. Hence it is reasonable to consider liquid sodium droplets are entrained into the water vapor flow. In the initial phase, the tube is surrounded by the liquid sodium as shown in Fig.1-(1). When the water vapor flows into the liquid sodium and reaches to the tube surface, the water vapor pushes the liquid sodium aside. But liquid film remains on the surface (Fig. 1-(2)). In this phase, the SWR takes place and the region is heated up and sodium hydroxide is generated at the liquid sodium surface or in gas phase as aerosols. As the reaction proceeds and the temperature increases, the liquid film becomes thinner (Fig. 1-(3)) and comes to the dryout of the tube surface (Fig. 1(4)). In this situation, the sodium runs out and the SWR goes down.

In safety consideration, what we are interested in is the tube temperature in the temperature rising phase and the dryout phase. As mentioned above, the reaction is dominant near the interface of the water vapor and bulk liquid sodium. As the

reaction proceeds, the region is covered with the reaction product hydrogen gas (see Fig.1(4)). It is a mechanism that mitigates the temperature increase. Subsequently, the water vapor replaces the hydrogen and the temperature begins to decrease if the water leakage continues (Fig. 1-(5)). There may be still small amount of liquid droplets of sodium since the ejecting water vapor entrains the liquid sodium droplets and carry them to the zone. The SWR continues, but it is mild and the temperature transient is benign. After the water leakage ceases, liquid sodium flows in again and the tubes are cooled down (Fig. 1-(6)). At this stage, the SWR is terminated.

2. COMPUTATIONAL MODEL

In the computer program, Navier-Stokes equations and chemical reaction equations are solved interactively. In addition, a dynamic equation of airborne particulates is coupled with the basic equations of thermal hydraulics. A source of the particulates is the chemical reaction products, i.e. sodium hydroxide and sodium oxide. Details of the computational models are given in Yamaguchi, Takata et al. (2006). In this section the authors describe the governing equations briefly.

2.1 Governing Equations

Governing equations for thermal-hydraulics are described. Taking the Reynolds average of the conservation equations, one obtains time-averaged equations as follows:

Mass conservation equation:

$$\frac{\partial \rho}{\partial t} + \text{div } \rho \bar{\mathbf{u}} = \sum_k S_k \quad (1)$$

Momentum conservation equation:

$$\frac{D\bar{u}_i}{Dt} = -\frac{1}{\rho} \text{grad } \bar{p} + \text{div} \left[\nu \text{grad } \bar{u}_i - \overline{u_i' u_j'} \right] + g_i - \frac{\bar{u}_i}{\rho} \sum_k S_k \quad (2)$$

Conservation equation of chemical species:

$$\frac{D\rho Y_k}{Dt} = \text{div}(\rho D_k \text{grad } Y_k) + S_k \quad (3)$$

Energy conservation equation:

$$\frac{D(\rho C_p \bar{T})}{Dt} = \text{div}(\lambda \text{grad } \bar{T} - \rho C_p \overline{u_i' T'}) + F + Q_R \quad (4)$$

The explanation of the variables is given in the nomenclature.

$\bar{\quad}$ and \quad' indicate the time average and fluctuating parts of a quantity, i.e. $u_i = \bar{u}_i + u_i'$. $S_k = \partial(\rho Y_k)/\partial t$ is the production term of species k by the chemical reaction.

Assuming the gradient-diffusion hypothesis, the Reynolds stress $\overline{u_i' u_j'}$ and the turbulent heat flux $\overline{u_i' T'}$ are defined using the turbulent viscosity and the turbulent thermal diffusivity. The equations for the turbulence energy and the

energy dissipation ratio are based on those for the low-Reynolds number two-equation model proposed by Yang and Shih (1993) that is a variation of Jones and Launder (1972) model and describes the near-wall effect. A zero-equation model is used with regard to the temperature field. According to the recommendation by Miyata (1995), Wassel-Catton equation is used for the turbulent Prandtl number. The functions and parameters appearing in the turbulence model are given by Yang and Shih (1993) and Miyata (1995).

2.2 Aerosol Dynamics

For evaluating the aerosol behavior, the evolution of the size distribution is calculated by solving the following general dynamic equation:

$$\begin{aligned} & \frac{\partial n(v)}{\partial t} + \text{div} \left(\frac{n(v)}{C_u(v)} \mathbf{u} \right) + \text{div}(n(v) \mathbf{U}) \\ &= \frac{1}{2} \int_0^v n(v') n(v-v') \beta(v', v-v') dv' \\ & - n(v) \int_0^\infty n(v') \beta(v, v') dv' + S(v) \end{aligned} \quad (5)$$

Aerosols are transferred in a thermal-hydraulic field by convection, diffusion, thermophoresis diffusiophoresis, and gravity fallout. In the transfer process of the aerosol mass, coagulation and sedimentation are major mechanisms of the change in the aerosol size distribution. The Brownian movement, the velocity difference of two aerosol particles, and the turbulence are the mechanisms for the coagulation. Gelbard and Seinfeld (1980) give details of the modeling of the coagulation process that is used in the present model.

The second term in the left hand side of Eq. (5) is the advection term due to the gas velocity. In this equation, $C_u(v)$ is the Cunningham correction factor to explain slip effect for smaller diameter particles than the mean free path of the gas. The third term in the left side of Eq. (5) represents mass transfer caused by applied forces to the aerosols. \mathbf{U} is the terminal velocity vector of particles, which are expressed as:

$$\mathbf{U} = \mathbf{U}_{dif} + \mathbf{U}_g + \mathbf{U}_{tp} + \mathbf{U}_{dp} \quad (6)$$

where the velocities with subscripts “dif”, “g”, “tp”, and “dp” are contributions from the Brownian diffusion, the gravity, the thermophoresis and the diffusiophoresis forces, respectively.

The aerosol source term is obtained based on the reaction rate evaluated by the chemical reaction model. One assumes that the statistical distribution of the primary aerosol diameter follows a lognormal distribution. The volume fraction of the aerosols is little and the interaction of the aerosols and the air flow can be neglected in the gas dynamics calculation.

2.3 Radiation Heat Transfer

We assume one-dimensional radiation heat transfer because we are dealing with pool surface phenomena. Using

gas temperature in i -th computational cell in vertical direction T_i numbered from the pool surface, one obtains the following equations regarding the volumetric heat generation rate Q_i of individual cell:

$$q_i = Q_i L_i = \varepsilon_i G_p \prod_{j=1}^{i-1} (1 - \varepsilon_j) + \varepsilon_i \sum_{j=i}^n \left\{ \varepsilon_j \sigma T_j^4 \prod_{k=i+1}^{j-1} (1 - \varepsilon_k) \right\} - 2\varepsilon_i \sigma T_i^4 \quad (7)$$

$$G_p = \varepsilon_p \sigma T_p^4 + (1 - \varepsilon_p) \sigma \sum_{j=1}^n \varepsilon_j T_j^4 \prod_{k=1}^{j-1} (1 - \varepsilon_k) \quad (8)$$

Here L_i and T_i are the cell size and local gas temperature, respectively, in i -th computational cell. G_p in the first term of the right side of Eq. (7) is the leaving flux from the pool surface and is given by Eq. (8). The pool surface emissivity is influenced by the surface conditions and $\varepsilon_p = 0.65$ is assumed according to the measurement by Hashiguchi, et al (1978).

The total gas mixture emissivity including aerosols is evaluated by Modak's radiative property model (Modak, 1979) and is applied to each computational cell.

$$\varepsilon_i = \varepsilon_a + \varepsilon_{gas} - \varepsilon_a \varepsilon_{gas} \quad (9)$$

where ε_{gas} and ε_a are the gas and the aerosol emissivity, respectively. ε_{gas} is calculated from the emissivity of the individual nontransparent gas with a correction for the overlapping of absorption bands from different gases. It can be assumed that the emissivity is equal to the absorptivity for aerosols. ε_a is evaluated according to Felske and Tien (1973) as a function of the local value of gas temperature, the mass density and the volume fraction of the aerosol.

3. SWR EXPERIMENT AND CODE VALIDATION

3.1 SWR in Counter Flow Diffusion Flame

To understand the SWR phenomena and to validate the numerical simulation method, a counter-flow laminar combustion experiment of SWR was performed by Yamaguchi, Takata, et al.(2006). Figure 2 shows the schematics of the sodium-water counter flow experiment.

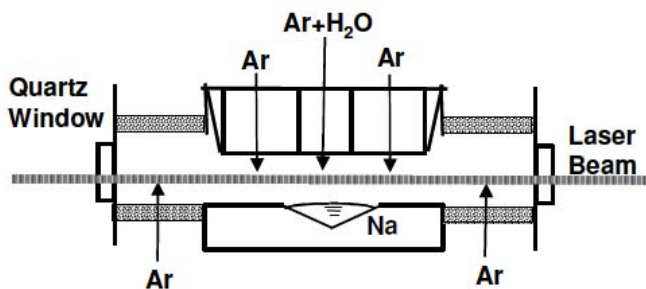


Fig.2 Sodium-water counter flow diffusion flame experiment

The outline of the experiment is as follows. A liquid sodium pool is heated up to 800K (less than the boiling point by 253K) so that the sodium evaporates slowly. Through the nozzle above the liquid pool surface, water vapor diluted to 0.7 volumetric % by argon gas flows out toward the sodium pool surface. Hence a counter flow diffusion flame is formed between the pool surface and the flow nozzle. It is important to keep the water vapor density at very low value for visualizing the flame zone. Otherwise, we cannot see the experimental cell inside because it is filled with white smoke (reaction product aerosol of sodium hydroxide). A strainer is installed at the exit of the mixture gas flow to provide flat velocity distribution. The reaction zone exists in-between the sodium pool and the strainer.

Figure 3 is the photo of the reaction zone as well as the aerosol mass concentration taken in the experiment. The sodium pool diameter is 0.03 m. In the experiment, existence of OH radical is measured by the Laser-Induced Fluorescence (LIF) technique. Blue color shows the OH radical fluorescence intensity. In the reaction, the water molecule decomposes first of all to produce OH radical which bonds with Na molecule. Therefore, the chemical reaction takes place in the region where OH fluorescence intensity is high. The region is located in 2 mm from the liquid sodium pool surface. The thickness of the reaction zone is approximately 1mm.

The aerosol concentration is visualized by the scattering of the laser beam from the aerosol particles. We can see the red light emission from the levitating aerosols. The aerosol existing area is like "crown" shape. This state is maintained for long time and is very stable. Figure 4 is the numerical results of the aerosol mass concentration. The numerical simulation is performed in two-dimensional geometry assuming axis symmetry.

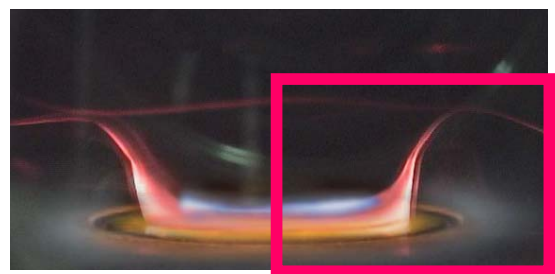


Fig. 3 Visualization of sodium-water reaction

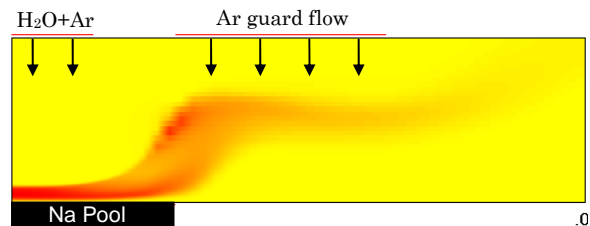


Fig. 4 Aerosol mass concentration

In Figs. 3 and 4, we can see the aerosol is dense above the liquid sodium pool. They move upward at the pool edge and are removed from the reaction zone. The flow field is in a mixed condition of forced and natural convection. Then the flow field and aerosol distribution are influenced by the temperature distribution as well. Also we can see is that the stable reaction flame is established. Since the saturated vapor pressure of sodium is very low, the flame location tends to adhere to the pool surface. It is important to lift the flame off the pool surface for the measurements.

However, trial-and-error process by a series of experiments is not practical to find out the best solution. Thus, the experimental condition (the geometry of the cell, boundary condition of flow velocities and temperatures) are optimized based on numerical simulations. To lift the flame up, double guard flows at different radial coordinates are used as shown in Fig. 2. One is an inner downward argon flow surrounding the H_2O+Ar flow. The inner guard flow is used to confine the water vapor in above-pool region. Another is an outer upward argon flow located at the peripheral of the experiment cell. The outer guard flow plays important role of lifting up the reaction flame.

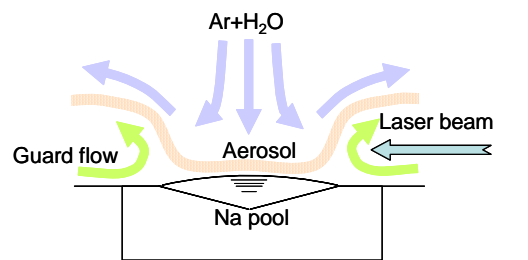
With this process, the flow and temperature fields surrounding the flame are adjusted so that the flame zone is detached away from the pool surface and the reaction products are removed from the reaction zone. The combination of the two guard flows is found to be appropriate to establish the optimal flow field for continuous chemical reaction and clear visualization and measurement. From the comparison of the numerical simulation and experimental observation, the performance of the present simulation is satisfactorily accurate and the optimization procedure of the flow and temperature and the experimental design works well. The dilution of water vapor and two guard flows enable sufficiently long duration time of the reaction. Accordingly one can extend the reaction duration time as long as 1 hour and achieve steady state reaction flame and no change in the liquid sodium level is observed during 5 minutes measurement. It is long enough for the laser measurement and visualization of the thermal-hydraulic field.

3.2 Modification of Sodium Pool Geometry

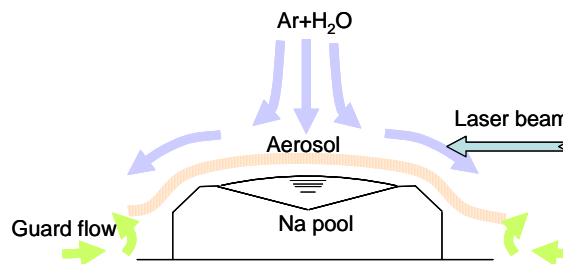
It is noted from Fig. 3 that the reaction zone is closed to the pool surface and the dense aerosol region exist above the sodium pool peripheral. The laser beam is irradiated in lateral direction permeating through the quartz window as shown in Fig. 2. Therefore there is concern that the thick aerosol region may deteriorate the transparency or visibility from the window. Thus a modification of the geometry of the edge of the sodium pool is considered.

Fig. 5(a) shows the original geometry and schematic flow pattern as well. Qualitative explanation of the flow field is

given in the following. The temperature of the outer guard flow is kept lower than the inner guard flow and the upward flow velocity is small. Therefore the outer guard flow direction turns to horizontal toward the pool center. Then it turns upward flow at the peripheral of the sodium pool. The upward guard flow is useful to remove the reaction product aerosol to the upper right of the figure and to make the flame visible. However, the aerosol region is stretched upward at the pool peripheral which may deteriorate the side view. Therefore, the edge of the pool is cut off as shown in Fig. 5(b) and the flow pattern is changed by adjusting the water vapor flow and the guard flow conditions. We expect the aerosol distribution as in Fig. 5(b) and better visibility from the window.



(a) Original geometry of the sodium pool



(b) Modified geometry of the sodium pool

Fig. 5 Modification of the sodium pool.

The bottom of Fig. 6 is the photo of the aerosols in the experiment with the modified geometry in Fig. 5(b). The water vapor concentration is 1.6 volumetric % and $Ar+H_2O$ flow velocity is 0.12m/s. It is seen that the upward stretching of aerosol at the pool peripheral is suppressed and is similar to that the authors expected in advance. The numerical simulation results of the aerosol density for the same condition as the experiment are shown in Fig. 7. It can be said that the aerosol distribution is in agreement with the experiment although quantitative comparison is necessary in the future.

The Laser Induced Incandescence (LII) measurement result is shown in the top of Fig. 6. The LII signal intensity was measured twice at 200ns and 300ns after the laser irradiation. The ratio of the two LII signal is shown in Fig. 6 top. The aerosol particle temperature rises by the laser irradiation followed by the cooling down as time goes. Hence

the ratio of the two LII signal intensities lies between zero and unity. Large particles with high thermal capacity are cooled down slowly and the LII signal ratio is close to unity. On the other hand, small particles with a little mass heat capacity are cooled down fast and the LII signal ratio approaches to zero. Therefore, the LII signal ratio corresponds to the particle diameter. Although quantitative measurement is not performed yet, we understand the particle is growing and the size becomes larger in the pool peripheral from Fig. 6.

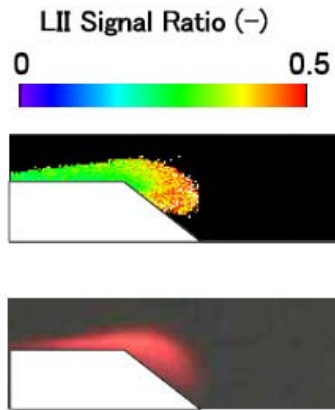


Fig. 6 Photo of the laser scattering by aerosols (bottom) and relative size of the aerosols measured by LII (top).

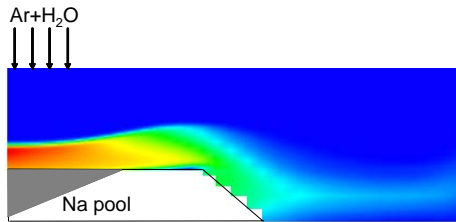


Fig. 7 Mass concentration of hydrogen

In the numerical simulation, the diameter of the incipient aerosol generated by the chemical reaction is assumed to be $0.5\mu\text{m}$. The aerosol diameter is divided into groups from $0.5\mu\text{m}$ to $100\mu\text{m}$ in lognormal scale. The small aerosol is subjected to the forces in small scale such as thermophoresis and diffusion (Yamaguchi and Tajima, 2003). Being driven by the forces, they move upward or downward before they coagulate to grow larger. Large aerosols follow the macroscopic gas flow.

Figure 8 shows the LIF measurement result and the OH radical concentration in arbitrary unit. We see that the reaction zone exists at 4mm above the pool surface at the pool center. If the existence of the OH radical corresponds to the reaction region, the reaction region lies above the dense aerosols. It is noted that the reaction zone is axis symmetric which verifies the assumption in the numerical simulation.

Numerical results of mass concentration distribution of sodium and water vapor along the vertical axis at the pool

center are shown in Fig. 9 to investigate the chemical reaction and mass concentration in the reaction zone. The solid lines are the computational results and the symbols indicate the experimental measurements. From the simulation results, the reaction flame locates at 2mm distant from the pool surface, where their mass concentrations approaches zero. No sodium vapor exists beyond the combustion flame and no water vapor below it as infinite reaction rate or flame sheet concept is assumed.

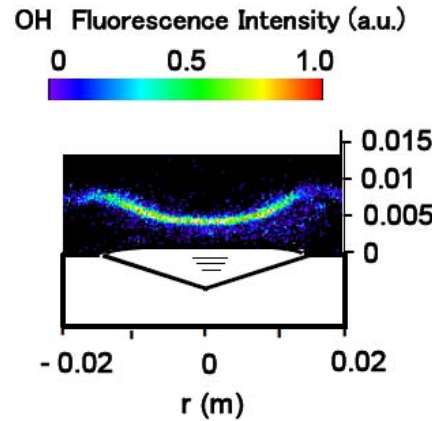


Fig. 8 Concentration of OH radical measured by LIF.

On the other hand, in the measurement the sodium vapor and the water vapor is almost consumed and disappears at 3 mm from the pool surface. There is a discrepancy between the experiment and numerical simulation in the flame location. From Fig. 8, the OH radical locates at 4mm above the pool which is more consistent with the experimental results in Fig. 9. More investigation is needed regarding the assumption of chemical reaction rate constant, the reaction process and/or reaction products.

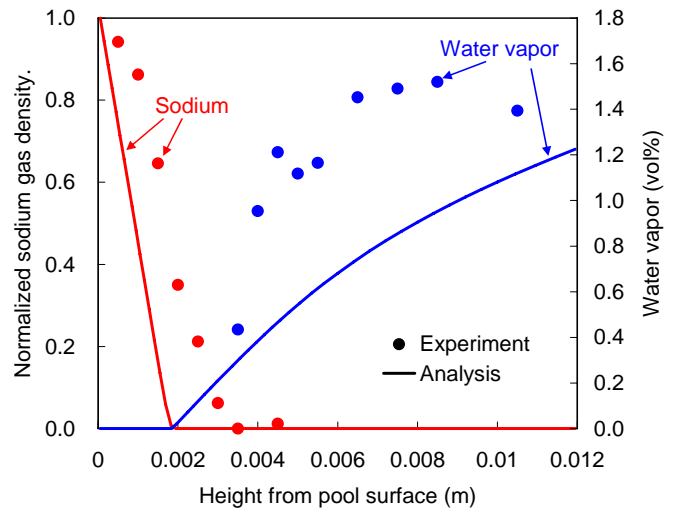


Fig. 9 Sodium and water vapor mass concentration

3.3 Proposal of Depressurized Experiment

To investigate the reason of the discrepancies between the analysis and the experiment mentioned in the previous section, the authors propose a depressurized experiment. We expect the flame moves upward and reaction region becomes thicker because of the decrease of the reactant gas density in the depressurized conditions. Therefore, the thermal hydraulic and chemical quantities can be measured with higher accuracy.

The flame location is influenced by the relationship of the water and sodium mass fluxes. To lift up the flame location above the pool surface, one needs to either increase the sodium mass flux and/or decrease the water vapor mass flux. With the depressurization, the sodium evaporation is enhanced and the sodium mass flux increases without ascending the pool temperature by improving the capacity of the heating unit. Current pool temperature condition (800K) is consistent with the actual situation in which the design temperature ranges from 625K to 743K. It is easy to control the water vapor mass flux by changing the approaching flow velocity and the water vapor concentration. Another advantage is that the gas density is decreased. The depressurization will decrease the frequency of water and sodium molecular collision. It will enlarge the reaction region thickness.

The authors performed sensitivity analyses to decide the most appropriate pressure and the experimental conditions. The minimum pressure is decided to be 25kPa considering the practicability of the experiment. Two analyses are shown in comparison with the ambient pressure (100kPa) case designated as Case 0. In Case 0 and Case 1, the water vapor concentration is assumed to be 2.7 volumetric % and flow velocity is 0.12 m/s. They are changed to 5.4 volumetric % and 0.06 m/s in Case 2. In the three cases, the water vapor mass flux is the same at the nozzle. The computational conditions are summarized in Table 1.

Table 1 Computational conditions.

	Pressure	Velocity	Water vapor
Case 0	100 kPa	0.12 m/s	2.7 vol%
Case 1	25 kPa	0.12 m/s	2.7 vol%
Case 2	25 kPa	0.06 m/s	5.4 vol%

Figure 10 shows the sodium and water vapor densities as a function of the distance from the pool surface. The flame location lies around 3mm from the pool surface in Case 1 and Case 2 while the flame location is below 1 mm in Case 0. Figure 11 shows the chemical reaction product concentration. Below the reaction flame is sodium-rich condition and Na₂O is the dominant reaction product. On the other hand, above the flame is water vapor rich and the NaOH is the dominant constituent. In the experiment, the constituent will be measured, which gives important information and insight as well as the validation data on the chemical reaction model.

As to the thickness of the reaction zone, we have little information on the reaction rate constant and fundamental reactions. In the present simulation, chemical equivalence model is used that assumes infinite reaction rate constant. Therefore, with this modeling, the thickness of the reaction zone is infinitely small. The expansion of the reaction zone is determined by the reaction rate constant and mobility of the reactants. If we observe the experimental results carefully, we may estimate the rate constant.

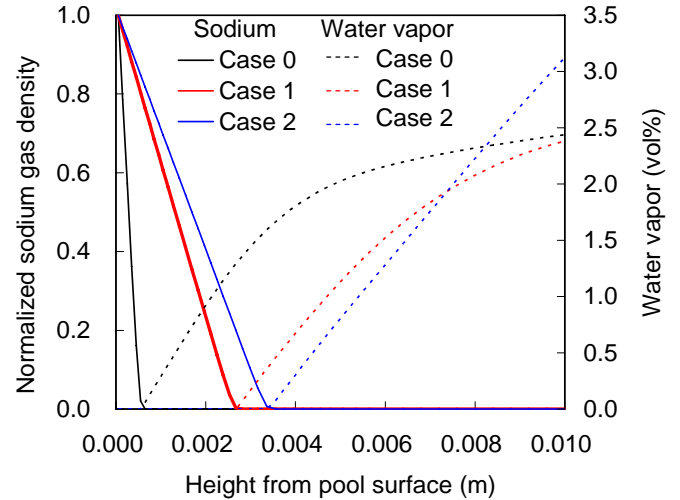


Fig. 10 Velocity vector above the pool surface

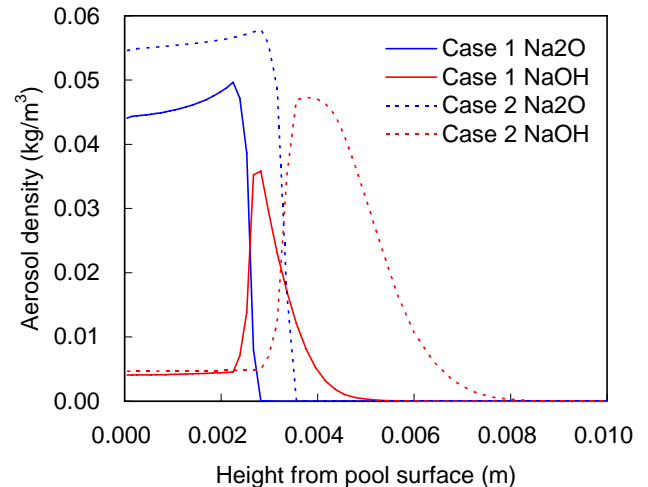


Fig. 11 Instantaneous temperature distribution

Figure 12 shows the aerosol mass density contours calculation. It is clear that the depressurization of the experimental cell lifts up the reaction flame which facilitates the laser measurement from the side window.

It is noteworthy that the reaction zone where OH radical exists is located above the aerosol (see Fig. 3, Fig. 6 and Fig. 8). Also, the existence of OH radical has been proven. An assumption that we employ is that the chemical reaction rate is

infinite, i.e. chemical equilibrium. As in Fig. 9, the water vapor and sodium vapor disappear at a flame plane with no thickness in the numerical simulation. On the other hand, the thickness of the OH radical seems to be an order of 1 mm as in Fig. 8. Further investigation is necessary by measuring the reaction zone thickness and investigating the relationship of the thickness and flow velocity or mass flux. With the information, the characteristic time of the convection flow and the chemical reaction will be quantified. The depressurized experiment is currently ongoing.

accuracy and to investigate and explain the reason of the disagreement. The authors propose a depressurized experiment. We expect the flame moves upward and reaction region becomes thicker because of the decrease of the reactant gas density in the depressurized conditions. It is expected based on the simulation that the experiment cell is depressurized to 25kPa, the stable and thick reaction flame is generated and the optic measurement is facilitated. Although the SWR is a complex phenomenon, the numerical simulation is useful and helpful to design an experiment to perform basic experiment to establish modeling for the safety analysis code.

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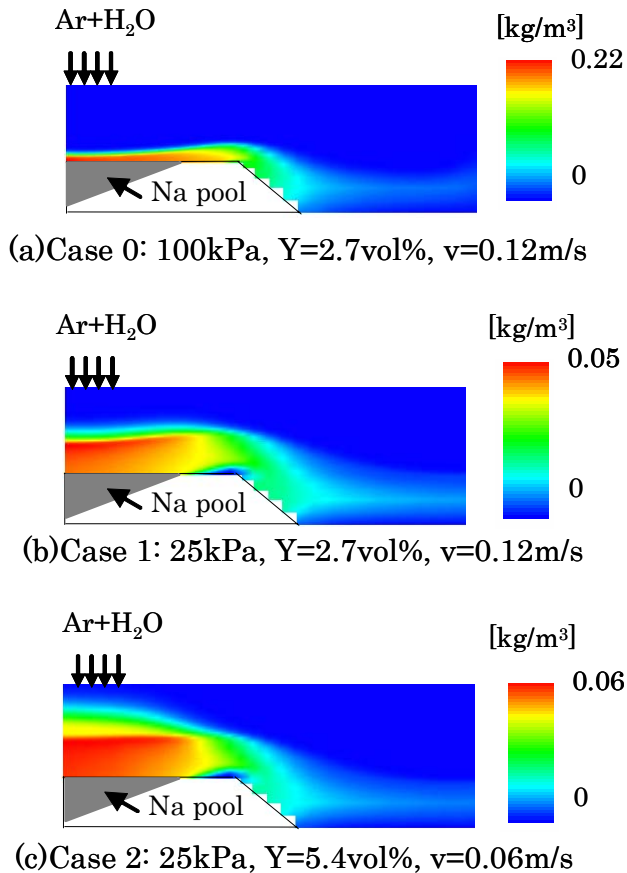


Fig. 12 Aerosol mass density for three cases.

CONCLUSIONS

In this paper, a new computer program has been developed for the gas phase reaction of the SWR. A counter-flow diffusion flame is studied by a numerical simulations and an experiment. The experiment conditions are decided with the numerical simulation so that the stable reaction flame is maintained for long time and physical and chemical quantities are measured. From the comparison of analysis and experiment, there exist discrepancies of the mass concentration distributions and location of the flame. It may be caused by the assumptions of chemical reaction model. Therefore, a new experiment is proposed to enhance the measurement